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Extremely Cold Winter Months in Europe (1951-2010)

Robert TWARDOSZ[1], Urszula KOSSOWSKA-CEZAK[2],
and Sebastian PEŁECH[1]

[1]Institute of Geography and Spatial Management, Jagiellonian University, Kraków, Poland; e-mail: r.twardosz@uj.edu.pl

[2]Department of Climatology, Faculty of Geography and Regional Studies, Warsaw University, Warszawa, Poland

Abstract

Investigation of extreme thermal conditions is important from the perspective of global warming. Therefore, this study has been undertaken in order to determine the frequency, timing and spatial extent of extremely cold months in winter time at 60 weather stations across Europe over a sixty-year period from 1951 to 2010. Extremely cold months (ECMs) are defined as months in which the average air temperature is lower than the corresponding multi-annual average by at least 2 standard deviations. Half of all the ECMs occurred in the years 1951-1970 (33 out of 67). The lowest number of ECMs was recorded in the decade 1991-2000, but since the beginning of the 21st century, their density and territorial extent has started to increase again. The extremely cold months with ECMs of the greatest spatial extent, covering at least one third of the stations (over 20 stations), included: February 1954 (22), February 1956 (36), January 1963 (25), and January 1987 (23 stations).

Key words: extremes temperature, temperature anomaly, winter seasons, Europe.

1. INTRODUCTION

Winter weather conditions, including air temperature, over the European land mass are chiefly determined by the North Atlantic Oscillation. During

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the positive phase of the NAO, relatively warm air from over the Atlantic flows in over Europe, whereas during its negative phase there is advection of cold, often freezing, Arctic air from the north or continental polar air from the east (Hirschi and Sinha 2007, Cattiaux *et al.* 2010, Wang *et al.* 2010, Ouzeau *et al.* 2011, Buchan *et al.* 2014). Longer spells of such advection, which are usually caused by the build-up of high-pressure blocking systems, lead to periods with anomalously low air temperatures in various parts of the continent (*e.g.*, Kossowska-Cezak 1997, Jaagus 2006, Bardin 2007, Isayev and Sherstyukov 2008, Sidorenkov and Orlov 2008, Ugryumov and Khar'kova 2008, Van den Besselaar *et al.* 2010). Such periods of strong declines in temperature have a number of effects on human life and activity and disturb the cycle of natural processes (Błażejczyk and McGregor 2007, Maignan *et al.* 2008). Descriptions of such freezing winters can be found in historical chronicles with accounts of the ice-bound Baltic Sea and rivers frozen down to the bottom or trees cracking in frost (Girguś and Strupczewski 1965). The most noteworthy winters in more recent times include three winters in the early 1940s which had a crucial effect on WWII. During one of them, in January 1942, the temperature on the Eastern Front dropped to –56°C (Brönnimann 2005).

Sometimes, extremely low temperatures last throughout the winter (Twardosz and Kossowska-Cezak 2016), and even continue until March and beyond, as during the extremely cold winter of 1928/29 in Poland (Gumiński 1931). Yet, extremely cold months tend to be much more frequent than ECWs. Therefore, the goal of the study is to determine the frequency and timing of extremely cold winter months (ECMs), as well as the areas where the respective extremely cold winter months were recorded in Europe between the mid-20th century and 2010. The study is a continuation of the authors' research into extremely cold winters in Europe (Twardosz and Kossowska-Cezak 2016). Literature includes other studies on the topic, *e.g.*, Baur (1954), Graham *et al.* (2006), Hirschi and Sinha (2007), Hirschi (2008), Cattiaux *et al.* (2010), Wang *et al.* (2010), Ouzeau *et al.* (2011), and Buchan *et al.* (2014), yet they concern different areas of Europe and different periods.

2. DATA AND METHODS

The study is based on average monthly values (between December and February) of air temperature in the years 1951-2010 recorded at 60 weather stations on the European continent and the British Isles (Table 1). For the most part, they are stations located in lowland areas up to 300 m a.s.l. As with earlier studies by the authors (Twardosz and Kossowska-Cezak 2013a, b; 2015a, b) the data for the research was obtained from the generally available European Climate Assessment & Dataset (ECA&D, www.eca.knmi.nl)

Table 1

Long-term average temperatures in winter months and the numbers of exceptionally cold months (ECMs) in Europe (1951-2010)

Station		T_{av} [°C]			No. of ECMs
No.	Name	Dec	Jan	Feb	
$\varphi < 40°N$					
1	Lisbon	12.0	11.3	12.2	3
2	Almeria	13.4	12.4	13.0	4
3	Crotone	10.5	9.3	9.5	5
4	Athens	12.0	10.3	10.6	5
$\varphi = 40\text{-}45°N$					
5	La Coruña	11.1	10.4	10.6	3
6	Madrid	6.5	6.0	7.5	6
7	Bordeaux	6.5	5.8	6.7	7
8	Barcelona	9.8	9.0	9.7	3
9	Marseilles	7.7	6.7	7.7	7
10	Rome	8.6	7.5	8.3	5
11	Split	9.2	7.8	8.2	7
12	Belgrade	2.7	0.9	2.9	7
13	Sofia	0.5	–1.2	0.8	6
14	Konstanca	3.2	0.9	1.8	8
15	Istanbul	8.3	6.1	6.3	6
16	Simferopol	2.3	–0.1	0.5	9
17	Sochi	8.2	6.2	6.3	3
18	Makhachkala	2.8	0.6	0.8	7
$\varphi = 45\text{-}50°N$					
19	Brest	7.2	6.4	6.4	7
20	Paris	5.2	4.4	5.3	11
21	Zurich	1.0	0.0	1.2	8
22	Würzburg	1.2	0.1	1.2	9
23	Vienna	1.3	–0.1	1.7	7
24	Debrecen	0.2	–1.8	0.3	9
25	Chernivtsi	–1.8	–3.9	–2.4	7
26	Zaporozhe	–1.4	–3.8	–3.1	9
27	Rostov on the Don	–1.4	–3.9	–3.4	5
28	Astrakhan	–2.1	–4.9	–4.6	7
$\varphi = 50\text{-}55°N$					
29	Valentia	7.8	6.9	6.8	6
30	London	5.3	4.5	4.5	7
31	De Bilt	3.4	2.5	2.8	11
32	Berlin	1.3	0.1	0.8	7

to be continued

Table 1 (continuation)

Station		T_{av} [°C]			No. of ECMs
No.	Name	Dec	Jan	Feb	
33	Warsaw	–0.7	–2.6	–1.8	8
34	Minsk	–3.7	–6.0	–5.3	6
35	Kiev	–2.3	–4.6	–3.8	8
36	Kursk	–5.1	–7.6	–7.4	7
37	Saratov	–6.6	–9.3	–9.3	6
38	Orenburg	–9.8	–13.1	–12.9	6
φ = 55-60°N					
39	Edinburgh	4.1	3.6	3.8	7
40	Oslo	–2.5	–3.7	–3.7	5
41	Copenhagen	2.4	0.8	0.6	6
42	Stockholm	–0.5	–2.3	–2.7	7
43	Liepaja	0.1	–2.0	–2.6	9
44	St. Petersburg	–4.1	–6.6	–6.7	7
45	Moscow	–5.7	–8.1	–7.6	8
46	Vologda	–8.6	–11.5	–10.7	3
47	Kazan	–9.0	–12.0	–11.4	7
48	Yekaterinburg	–11.3	–13.7	–12.3	7
φ = 60-65°N					
49	Bergen	2.7	2.0	1.8	8
50	Trondheim	–1.4	–2.6	–2.3	6
51	Vaasa	–4.6	–6.6	–7.3	7
52	Kajaani	–8.5	–11.1	–11.1	7
53	Arkhangelsk	–9.6	–13.0	–12.0	7
54	Syktyvkar	–11.9	–15.0	–13.4	4
55	Ivdel	–16.0	–18.8	–16.6	6
φ = 65-70°N					
56	Bodö	–0.6	–1.6	–1.9	4
57	Sodankyla	–11.9	–13.9	–13.2	4
58	Naryan-Mar	–13.8	–17.6	–17.3	6
59	Pechora	–15.7	–18.9	–17.5	7
φ > 70°N					
60	Vardö	–3.2	–4.5	–5.0	3
Σ					387

(Klein Tank *et al.* 2002). The data in the database offers a very high spatial resolution and a large number of complete, good-quality data series, which are verifiable for homogeneity (Wijngaard *et al.* 2003). The database has been also used by many other researchers (*e.g.*, Cony *et al.* 2008, Van den

Besselaar *et al.* 2010, Moberg *et al.* 2006). For the purposes of the present study, extremely cold months (ECMs) are those during which the average temperature is lower than the multi-annual (1951-2010) average temperature at a given station by at least 2 standard deviations ($t \leq t_{av} - 2\sigma$). The authors have previously used the method to investigate extremely cold winter seasons and extremely hot summer seasons and months (Twardosz and Kossowska-Cezak 2013a, b; 2015a, b; 2016). This is a relative method, in which reference is made to the average thermal conditions in a given area. This criterion has been used by many other researchers, including Hansen *et al.* (2012).

3. FREQUENCY OF EXTREMELY COLD WINTER MONTHS

In the years 1951-2010, 387 cases of extremely cold months (ECMs) were recorded across the 60 stations in Europe, which occurred during 67 months of the 60-year period. On average, one ECM occurred at nearly 6 stations (5.8). Extremely mild months, the existence of which was determined by an analogous method, were half as frequent (34 months), and the areas they covered were half as big – 3 stations (3.1) (Kossowska-Cezak *et al.* 2016). As has been shown by the authors (Twardosz and Kossowska-Cezak 2016), the years 1951-2010 saw 103 cases of extremely cold winters. Thus, the ratio of the number of ECMs to ECWs is 3.75, while the same ratio for extremely mild months is merely 2.62. Furthermore, among the 103 cases of extremely cold winters in 19 cases there were no ECMs at all, and in 50 winters there was only one ECM. On the other hand, among the 387 ECMs only 123 occurred during extremely cold winters, and the other 264 ECWs were not connected to such winters. The above figures clearly indicate that individual ECMs are a frequent phenomenon in Europe.

Table 2

Number of exceptionally cold months (ECMs) and the number of stations where ECMs were recorded in Europe (1951-2010)

Period	Number of months	Number of stations
1951/52* – 1959/60	16	99
1960/61 – 1969/70	17	99
1970/71 – 1979/80	9	42
1980/81 – 1989/90	9	85
1990/91 – 1999/2000	7	17
2000/01 – 2009/10	9	45
1951/52 – 2009/10	67	387

*⁾No data from winter 1950/1951.

Table 3

Exceptionally cold winter months (no. of stations) in Europe (1951-2010)

Winter	Dec	Jan	Feb	Σ
1950/51	x	–	1	(1)
1951/52	–	1	–	1
1952/53	–	2	1	3
1953/54	3	11	22	36
1954/55	–	–	1	1
1955/56	12	–	36	48
1956/57	1	3	–	4
1957/58	1	–	–	1
1958/59	2	–	1	3
1959/60	1	–	–	1
...				
1962/63	6	25	7	38
1963/64	9	6	–	15
1964/65	–	–	4	4
1965/66	1	2	11	14
1966/67	1	–	–	1
1967/68	1	4	–	5
1968/69	2	8	2	12
1969/70	9	–	2	11
1970/71	3	–	–	3
1971/72	–	10	–	10
...				
1975/76	–	1	3	4
1976/77	1	2	–	3
1977/78	–	–	1	1
1978/79	16	4	–	20
...				
1980/81	1	2	–	3
1981/82	7	–	–	7
...				
1984/85	2	19	19	40
1985/86	1	–	11	12
1986/87	–	23	–	23
...				
1990/91	1	–	–	1
1991/92	6	–	–	6
...				
1995/96	1	–	–	1
...				

to be continued

Table 3 (continuation)

Winter	Dec	Jan	Feb	Σ
1997/98	–	–	3	3
1998/99	4	1	–	5
1999/2000	–	1	–	1
...				
2001/02	10	–	–	10
2002/03	14	–	1	15
...				
2005/06	1	2	–	3
...				
2007/08	–	1	–	1
...				
2009/10	1	2	–	3
2010/11	13	x	x	(13)
No. of stations with ECMs	131	130	126	387
No. of ECMs	29	21	17	67

In the six decades, from 1951 to 2010, the frequency of ECMs fluctuated significantly (Table 2). Half of the ECMs (33 out of 67) and over half of their cases (the number of stations where ECMs were recorded was 198 out of 387) were recorded in the first two decades. Those years saw 3 out of the 4 ECMs that were recorded by more than 20 stations (Table 3). In the decades that followed, the number of ECMs remained quite steady (7-9 in 10 years), but the decade 1980/81-1989/90 was distinguished by a relatively high number of cases (85), with another ECM recorded by 20 stations and 2 ECMs by 19 stations. The last decade of the 20th century saw the least number of ECMs, and clearly the lowest number of cases, *i.e.*, merely 17, which means that the ECMs in that decade covered smaller areas. In the first decade of the 21st century, ECMs registered by 10 or more stations started to slowly re-appear. The first decade of the 21st century also saw the greatest number of extremely mild winter months (10 out of 34) and of their cases (40 out of 105). It was the only decade to see fewer ECMs than mild months (9 and 10, respectively), while in the first 2 decades under study there were 4 times more of them (33 and 8, respectively).

The number of ECMs at individual stations varied from 3 to 11, but typically ranged from 6 to 7 (Table 1). The lowest numbers (3-5 per station) were recorded in the southernmost parts of Europe, mainly in the Iberian Peninsula. ECMs were most numerous in the central part of the continent, in the area stretching from the Scandinavian Peninsula to the Balkans, with a wedge reaching westwards as far as France – more than 8 ECMs, with a peak of 11 in Paris and De Bilt.

4. SPATIAL EXTENT AND THERMAL CHARACTERISTICS OF ECMS

A calendar of ECMs is presented in Table 3, showing the year and month, as well as the number of cases, *i.e.*, stations where an ECM occurred. As can be seen in the calendar, a large proportion of the ECMs covered a very small area, only 1-3 stations, that is, not more than 5% of the stations. There were 40 such montfIGhs out of the 67 in the 6 decades. Another 7 ECMs were recorded by not more than 6 stations (10%). These 47 ECMs comprising not more than 10% of the stations will be largely disregarded in the study presented below. A compilation of the remaining 20 ECMs is given in Table 4. It is worth noting that out of the 34 extremely mild winter months (not shown), only 5 covered more than 10% of the stations (December 1960 – 7 stations, February 1990 – 19, February 2002 – 7, December 2006 – 10, and January 2007 – 13 stations).

The first 10-year period of 1951-1960 recorded nearly ¼ of all the ECMs – 16 out of 67, but most of them covered very small areas or only a single station. Only 4 ECMs had a larger extent.

The ECM of January 1954 covered 11 stations in south-central Europe (Table 4). The temperature anomaly Δt ranged between –3.2°C in Split and –4.4°C in Istanbul, and –6 to –8°C in the remaining area, with the greatest anomaly in Zaporizhia, where $\Delta t = -8.7$°C. In Split and Istanbul, the average monthly temperatures were above zero, and the lowest temperature was recorded in Saratov, where $t = -17.1$°C.

The next month of the same year, the ECM of February 1954, covered 22 stations (Fig. 1, Table 4) which were nearly all the same as in previous month plus east and central Europe from Berlin and Vienna to Yekaterinburg and Makhachkala. The temperature anomaly Δt ranged between –4.3°C in Istanbul (which was the only station where t was above zero), –5 to –6°C in the west and –9 to –11°C in the east with the greatest anomalies in Astrakhan $\Delta t = -14$°C (the largest of all the months) and Rostov $\Delta t = -13.6$°C. The lowest average temperature was recorded in Orenburg $t = -24.4$°C. February 1954 was among the coldest months in the 60-year period. More temperature characteristics from selected weather stations are presented in Table 5.

The ECM of December 1955 covered 12 stations in southeastern Europe. A temperature anomaly of $\Delta t = -5$°C was seen in Bodö and Vardø only, with the other stations recording anomalies of more than –10°C, including Syktyvkar $\Delta t = -13.5$°C and Pechora $\Delta t = -13.1$°C. The lowest monthly average temperatures were in Pechora $t = -28.8$°C and in Ivdel $t = -28.7$°C.

Table 4

Exceptionally cold winter months in Europe recorded at 7 or more stations (1951-2010)

Year	Month	No. of stations	Stations (no. according to Table 1)	ECW
1954	Jan	11	11, 14, 15, 16, 24, 25, 26, 27, 35, 36, 37	ECW 1953/54 at 16 stations; 3 ECMs each in Istanbul (15) and Simferopol (16)
	Feb	22	2, 12, **14**, 15, 16, **18**, 23, 24, 25, **26**, **27**, **28**, 32, 33, 34, 35, 36, 37, 38, 43, 47, 48	
1955	Dec	12	44, 45, **46**, 47, 48, 52, 53, 54, 55, 56, 59, 60	ECW 1955/56 at 10 stations
1956	Feb	36	1, 2, 3, **5**, **6**, **7**, **8**, **9**, **10**, **11**, 12, 13, 14, 16, **19**, **20**, **21**, **22**, **23**, 24, 25, 26, 27, **31**, **32**, 33, 34, 35, 36, 37, 41, 43, 44, 45, 47, 48	
1963	Jan	25	7, 11, 12, 13, 14, 19, 20, 21, 22, 23, 24, 25, 26, **29**, **30**, **31**, 32, 33, 34, 35, 36, 39, 41, 45, 49	ECW 1962/63 at 24 stations. 3 ECMs each in Paris (20), Wurzburg (22), and De Bilt (31)
	Feb	7	19, 20, 22, 30, 31, 39, 49	
1963	Dec	9	12, 19, 20, 21, 22, 23, 24, 25, 31	ECW 1963/64 at 3 stations
1966	Feb	11	42, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59	ECW 1965/66 at 7 stations
1969	Jan	8	28, 37, 38, 45, 47, 48, 54, 55	ECW 1968/69 at 7 stations
1969	Dec	9	9, 11, 20, 21, 22, 23, 32, **33**, 43	ECW 1969/70 at 4 stations
1972	Jan	10	16, **18**, 26, 27, **28**, 37, 38, 47, 48, 55	
1978	Dec	16	34, 36, 40, 42, 43, 44, 45, 46, 47, 50, 51, 52, 53, 54, 58, 59	ECW 1978/79 at 6 stations
1981	Dec	7	31, 39, 40, 41, 49, 50, 56	
1985	Jan	19	6, 7, **8**, 9, 10, 20, 21, 22, 23, 30, 31, 41, 42, 43, 51, 52, 53, 57, 58	ECW 1984/85 at 9 stations
	Feb	19	14, 15, 16, 17, 24, 26, 33, 34, 35, 42, 43, 44, 51, 52, 53, 55, 56, 57, 59	
1986	Feb	11	19, 20, 21, 22, 29, 30, 31, 32, 33, 39, 49	
1987	Jan	23	7, 9, 19, 20, 21, 30, 32, 33, 34, 35, 36, 40, 41, 42, 43, 44, 45, **46**, 49, 50, 51, 52, 57	
2001	Dec	10	4, 8, 11, 12, **13**, 14, 24, 25, 26, 35	
2002	Dec	14	16, **18**, 25, 26, 27, **28**, 33, 35, 36, 37, 38, 43, 45, 47	
2010	Dec	13	19, 20, 22, 29, 30, 31, 32, 39, 40, **41**, 42, 49, 50	

Notice: Station numbers printed in bold mean that the average winter temperature at that station met the formula $t \le t_{av} - 3\sigma$.

Table 5

Thermal characteristic of the extremely cold winter months (ECMs) in Europe (1951-2010)

Station		Temperature [°C]				No. of days with T_{max}		
No.	Name	$T_{av.}$	Δt	T_{max}	T_{min}	<0°C	<–10°C	<–20°C
1954 February								
15	Istanbul	2.0*	–4.3	5.4	–1.3	3	–	–
28	Astrakhan	**–18.6**	–14.0	–12.8	–23.4	28	25	–
35	Kiev	–12.9	–9.1	–9.2	–16.6	27	15	–
47	Kazan	–21.6	–10.2	–17.7	–26.0	28	26	9
1956 February								
1	Lisbon	**7.8***	–4.4	11.8	3.9	–	–	–
20	Paris	**–3.5***	–8.8	0.3	–7.2	14	–	–
23	Vienna	**–8.5***	–10.2	–5.2	–11.7	26	4	–
32	Berlin	**–8.4***	–9.2	–5.1	–12.7	25	3	–
35	Kiev	–13.1*	–9.3	–8.7	–16.5	24	14	1
44	St. Petersburg	–14.8*	–8.1	–10.1	–19.3	27	10	5
45	Moscow	–18.5*	–10.9	–13.9	–22.8	29	19	5
48	Yekaterinburg	–20.1*	–7.8	–15.5	–24.1	29	22	8
1963 January								
20	Paris	–1.6*	–6.0	0.7	–3.9	13	–	–
29	Valentia	**2.3***	–4.6	4.9	–0.3	–	–	–
32	Berlin	–7.3*	–7.4	–4.4	–10.7	24	1	–
41	Copenhagen	–4.5	–5.3	–2.2	–6.9	22	–	–
45	Moscow	–15.9	–7.8	–12.9	–19.5	31	20	2
1978 December								
40	Oslo	–8.0	–5.5	–5.9	–10.3	31	4	–
59	Pechora	–29.6*	–13.9	–25.2	–33.8	31	29	22
1985 January								
10	Rome	4.1*	–3.4	8.1	0.0	3	–	–
53	Arkhangelsk	–25.3*	–12.3	–20.1	–29.7	31	25	18
58	Narjan Mar	–27.3*	–9.7	–22.7	–31.9	29	27	23
1985 February								
16	Simferopol	–8.0*	–8.5	–3.2	–12.1	18	6	–
57	Sodankyla	–25.1*	–11.9	–19.6	–31.1	28	25	10
1987 January								
44	St. Petersburg	–17.9*	–11.3	–15.0	–21.0	31	20	10
49	Bergen	–2.9	–4.9	–0.5	–5.6	15	1	–
2002 December								
18	Machaczkała	**–5.4***	–8.2	–0.9	–9.9	16	1	–
35	Kiev	–8.4*	–6.1	–5.4	–11.4	28	1	–
2010 December								
29	Valentia	**4.2***	–3.6	6.8	1.5	–	–	–
42	Sztokholm	–6.6*	–6.1	–4.2	–9.3	27	1	–

*) The lowest in 60 years;

Notice: A value in bold means that the temperature meets the criterion $t \le t_{av} - 3\sigma$.

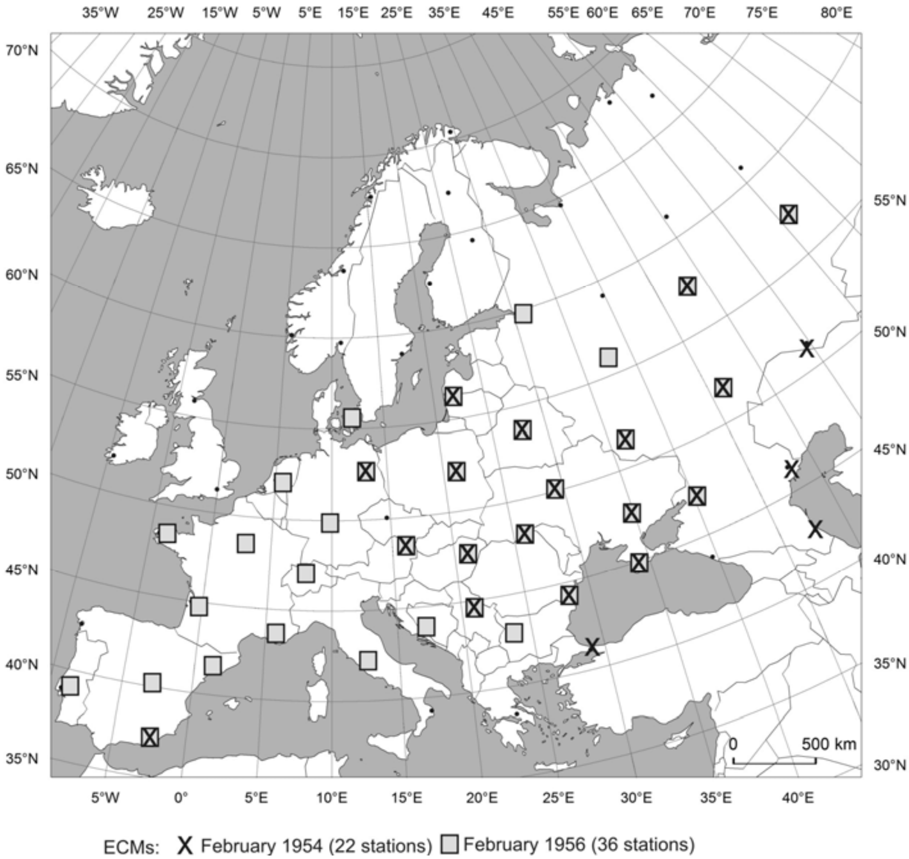

Fig. 1. Stations with extremely cold months: February 1954 (22 stations) and February 1956 (36 stations).

February 1956 was another ECM in the same winter of 1955/56. It was the ECM that extended over the largest number of stations during the 6 decades, *i.e.*, 36 stations in southern and central Europe (Fig. 1, Table 4). In Saint Petersburg, Moscow, Kazan, and Yekaterinburg it was the second ECM during the same winter. It was one of the coldest months in the 6 decades under study. The deviation of average monthly temperature, t, from the multi-annual average, t_{av}, in the ECM of February 1956 exceeded 3 standard deviations at 14 stations. A temperature anomaly Δt of approx. –3 to –6°C was only recorded in the westernmost and southernmost areas (average temperature t above zero), while in the remaining area Δt was from –8 to –11°C, with the greatest value in Saratov, $\Delta t = -11.3$°C, where the lowest temperature, $t = -20.6$°C, was also recorded.

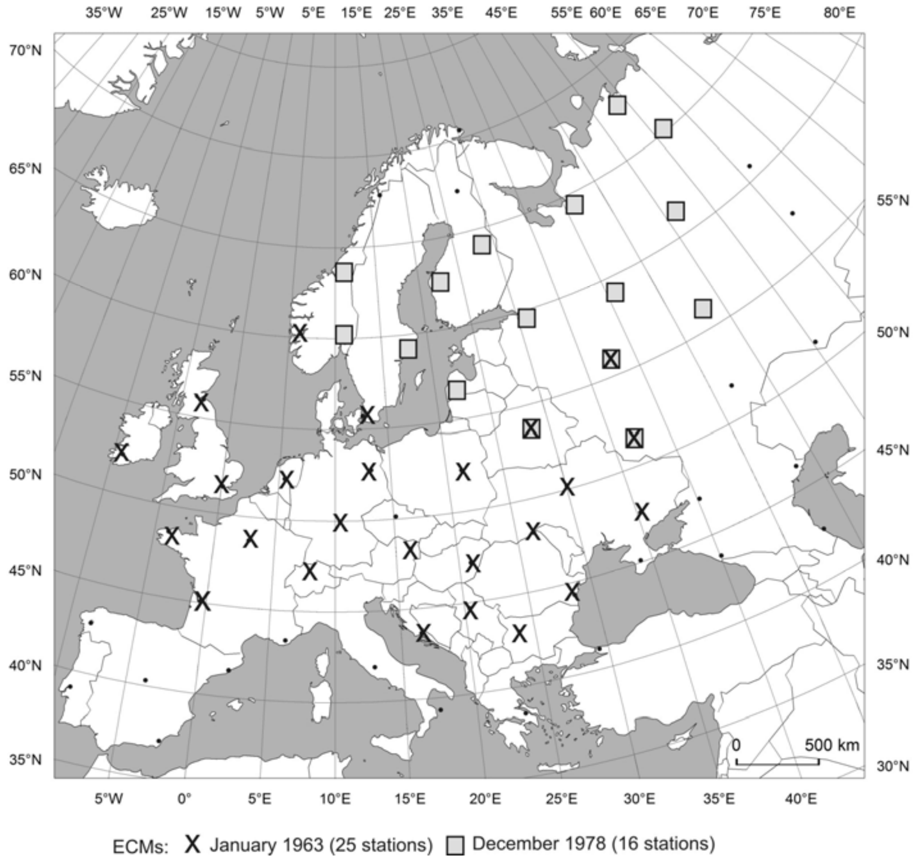

Fig. 2. Stations with extremely cold months: January 1963 (25 stations) and December 1978 (16 stations).

In the next decade, 1960/61 − 1969/70, ECMs were as frequent as in the previous one (17 ECMs) yet with more ECMs covering a greater territory.

The ECM of January 1963 covered 25 stations (in 6 stations December 1962 was also an ECM) in western and central Europe (Fig. 2, Table 4). In most of the stations, it was the coldest January in the 60-year period and in many the coldest winter month. The temperature anomaly Δt ranged between –4 and –6°C in the west and south (overall, t in the westernmost areas was above zero), and in the east between –8 and –9°C, including the greatest anomaly in Warsaw, $\Delta t = –9.8$°C. The lowest mean temperature was recorded in Kursk, $t = –16.8$°C. The lower negative air temperature anomalies in winter in Western Europe are attributable to the mitigating effect of the waters of the Atlantic Ocean (Hirschi and Sinha 2007), as opposed to the cooled land in central, and even more so, Eastern Europe, which is conducive to significant falls in air temperature.

The ECM of February 1963 was recorded by 7 stations of northwestern Europe and was a second ECM in the same winter. The temperature anomaly Δt was approx. from –4 to –6°C. The lowest mean temperature was in Würzburg, $t = -5.4$°C.

The winter of 1962/63 was extremely cold at 24 stations in Western Europe. The winter was among those with the largest extent and one of the two coldest (in addition to the winter of 1955/56) in the 60-year period, and in the southernmost and westernmost areas of the continent – the only extremely cold winter during the 6 decades.

The ECM of December 1963 occurred at 9 stations in a band running between Brest and De Bilt in the northwest and Belgrade and Chernivtsi in the southeast. The temperature anomaly Δt was between *ca.* –3°C in the westernmost part (here temperature t was above 0°C, in Brest $t = 4.2$°C) and –5°C in the east, including Vienna $\Delta t = -5.7$°C. The lowest temperature, in Chernivtsi, was $t = -6.6$°C.

January 1964 was an ECM in 6 stations and February 1965 in 4 stations in the south of Europe. A larger extent was that of the ECM of February 1966, which was registered by 11 stations on the Scandinavian Peninsula and in northwest Russia. The temperature anomaly Δt was between *ca.* –7°C on the coast of the Scandinavian Peninsula and –12 – –13°C in the northwestern areas covered by that ECM. The highest, $\Delta t = -12.9$°C, and the lowest temperature of all the months under study, $t = -30.2$°C, was recorded in Naryan-Mar, and not much higher in Pechora, $t = -29.8$°C.

Again, 4 stations within the same area that recorded the ECM of January 1968 (Δt from ~ –9 to –11°C), and another ECM in January 1969 at 8 stations in southeastern Europe, including, as in February 1966, Syktyvar and Ivdel. The temperature anomaly Δt was from –8 to –11°C, with $\Delta t = -11.7$° in Orenburg. The lowest average monthly temperature, $t = -27.1$°C, was recorded in Ivdel, the lowest $\Delta t = -13.0$°C in Astrakhan. In the easternmost areas, it was the coldest January in the 60-year period.

In the same year, December 1969 was an ECM covering 9 stations in Western Europe. The temperature anomaly in Marseilles, Split and Paris Δt was between –3 and –4°C (with the average temperature above zero, up to 6°C in Split) and –6 and –7°C in the east, with the greatest anomaly in Warsaw, $\Delta t = -7.8$°C; Warsaw also recorded the lowest temperature, $t = -8.5$°C. It was the coldest December in the years 1951–2010 in Zurich, Berlin, and Warsaw.

The decade that followed was characterised by far fewer ECMs. There were 9 of them, including only two ECMs recorded by more than 10% of the stations. This included the ECM of January 1972, which occurred at 10 stations in southeastern Europe. Despite the rather vast area, Δt was quite uniform, ranging between approx. –8 and –10°C, Simferopol being the only exception, with $\Delta t = -7.1$°C (and with the highest $t = -7.0$°C). The greatest anomalies were recorded in Astrakhan, $\Delta t = -10.6$°C, and Yekaterinburg, $\Delta t = -10.5$°C. The lowest average temperature was recorded in Ivdel $t = -28.2$°C. Here, as well as in some other stations in the east, the coldest January of the six decades under study was recorded.

The ECM of December 1978 comprised 16 stations in the Scandinavian Peninsula and in northeastern Europe (Fig. 2, Table 4). The temperature anomaly Δt in the westernmost and southernmost areas of ECMs ranged from ~ –5 to –7°C (the lowest in Stockholm $\Delta t = -4.9$°C, where the highest $t = -5.4$°C was also registered). The anomaly in the north was more than –10°C, the greatest in Pechora, $\Delta t = -13.9$°C, which also saw the lowest temperature, $t = -29.6$°C. For some stations it was the coldest December in the six decades. In the north, the winter of 1978/79 was extremely cold throughout (Twardosz and Kossowska-Cezak 2016).

The 1980s also saw 9 ECMs, but out of these 5 covered more than 10% of the stations. The smallest area, 7 stations, was that of the ECM of December 1981, which occurred in northwestern Europe, including the western areas of the Scandinavian Peninsula. The temperature anomaly Δt was between approx. –4 and –5°C in the southern areas covered by the ECM (De Bilt, Copenhagen) and –6 and –7°C in the north, with the greatest anomaly in Trondheim, $\Delta t = -7.3$°C. It was the coldest period in the six decades for the coast of the Norwegian Sea, with the lowest average temperature $t = -9.0$°C being recorded in Oslo.

January 1985 and February 1985 were ECMs during the winter of 1984/85, which extended over large areas – 19 stations each (Fig. 3, Table 4). The ECM of January 1985 covered southwestern Europe, the Baltic countries and the northernmost and easternmost areas. The temperature anomaly Δt ranged from –2 to –4°C in the south and west, and –5 to –7°C in the central part. The northernmost and easternmost areas had a Δt of ~ –10 to –12°C, with the highest anomaly in Kajaani $\Delta t = -13.2$°C. The average monthly temperature on the coast of the Mediterranean Sea was above zero, and below –20.0°C in the northeast, with the lowest temperature in Naryan Mar, $t = -27.3$°C. Naryan Mar also saw the coolest January in the 60-year period.

The ECM of February 1985 occurred in the same 6 stations as the previous month on the Baltic Sea, in Finland and Arkhangelsk, reaching beyond them to the south of the above area, across Poland and Belarus, as far as the coast of the Black Sea (Fig. 3, Table 4), as well as to the north to Pechora and Ivdel. The temperature anomaly of Δt was only lower than –5°C in Bodö, Istanbul and Sochi, and ranged between approx. –8 and –11°C at the

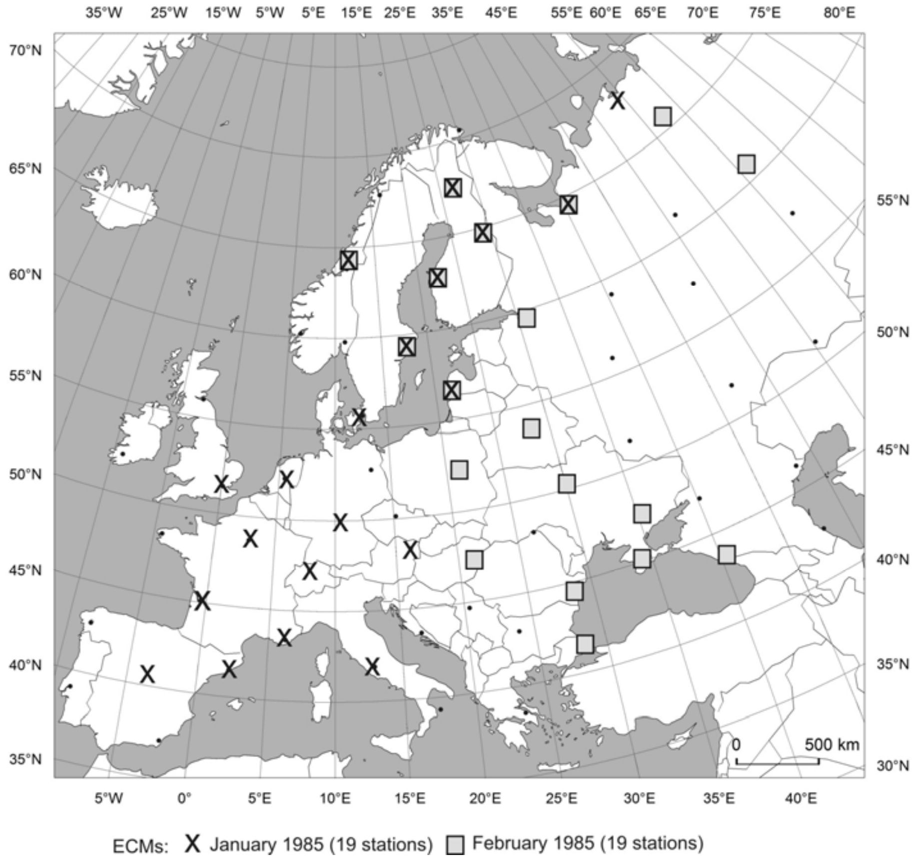

Fig. 3. Stations with extremely cold months: January 1985 (19 stations) and February 1985 (19 stations).

other stations, with the greatest anomaly, Δ*t* = –11.9°C, in Sodankylä. Temperatures were above zero in Istanbul and Sochi (but in Simferopol *t* = –8.0°C), and below –20ºC in the north, with the lowest temperature in Pechora, *t* = –28.5°C. At some individual stations, including Istanbul and Saint Petersburg, it was the coldest February in the 60-year period.

In the following year, the ECM of February 1986 also occurred. It spanned 11 stations in Western Europe. The temperature anomaly in the westernmost parts (Valentia, Edinburgh, Bergen), showed a Δ*t* from ~ –4°C with up to –6 – –7°C in the rest of the area and with the greatest anomaly, Δ*t* = –7.4°C, in Warsaw. Warsaw also recorded the lowest temperature *t* = –9.6°C. The temperature *t* in Valentia and Brest was above 0°C.

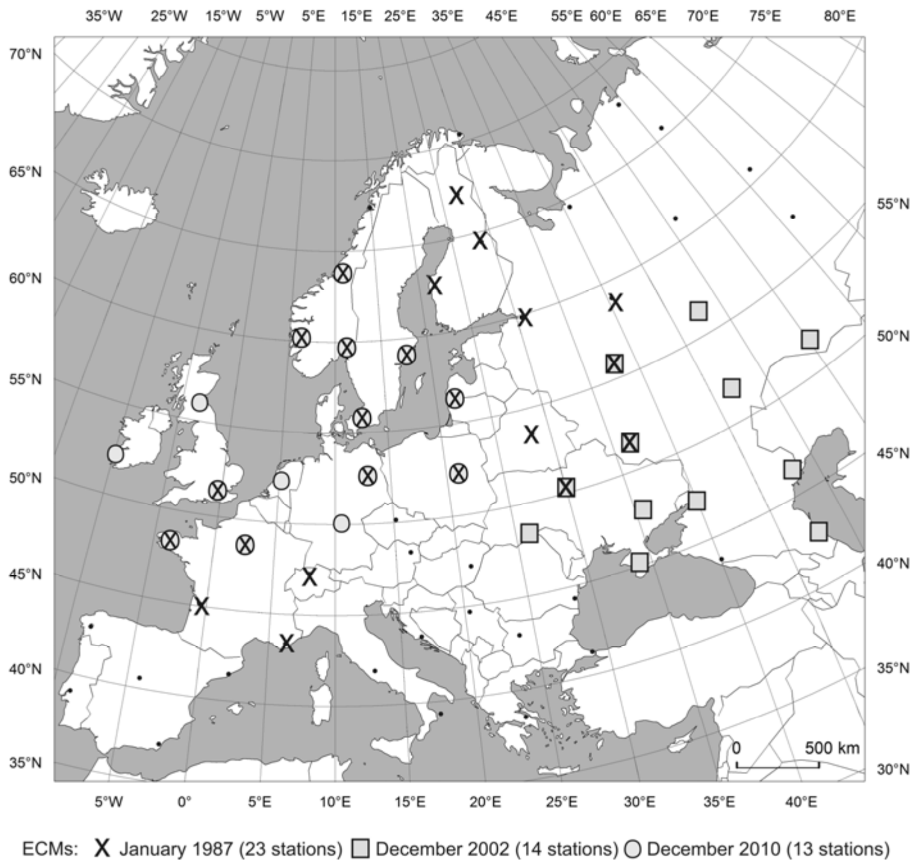

Fig. 4. Stations with extremely cold months: January 1987 (23 stations), December 2002 (14 stations), and December 2010 (13 stations).

The ECM of January 1987 was one of the most extensive ECMs in the 1951-2010 period, stretching over 23 stations from the western coast of Europe to Moscow and the Scandinavian Peninsula (Fig. 4, Table 4). The temperature anomaly Δt in the westernmost coastal areas was approx. –4 – –5°C (average temperature t above zero). In the interior of the continent Δt was ~–7 to –10°C with the highest, $\Delta t = -13.0$°C, in Vologda (the latter also recorded the lowest average temperature, $t = -24.5$°C) and Vaasa $\Delta t = -12.0$°C. In the central part of the area covered by the ECM, it was the coldest month in the 60-year period.

The last decade in the 20th century saw 7 ECMs, but none of them covered an area with more than 10% of the stations.

In the first decade of the 21st century the frequency of ECMs started to increase slightly again. There were 9 of them, including 3 with a greater extent than in the previous decade.

The ECM of December 2001 was recorded by 9 stations in south-central Europe. The temperature anomaly Δt in the southern stations (Athens, Split) was ~ –3°C (with temperature t above 5°C), and inside the continent it was approx. –5°C, with the largest anomaly in Sofia, $\Delta t = -6.3$°C. The lowest average temperature in Kiev was $t = -7.3$°C.

The next ECM of December 2002 spanned a vast area of southeastern Europe with 14 stations (Fig. 4, Table 4). Temperature anomaly Δt in the west of the area was between –5 and –6°C, in the east it was between –8 and –9°C, with the greatest anomaly occurring in Orenburg, $\Delta t = -9.7$°C, where the lowest average monthly temperature was also recorded at $t = -19.5$°C. In Makhachkala and Astrakhan the deviation of average monthly temperature t from the multi-annual average exceeded 3 standard deviations. At most of the stations (except for the westernmost areas), it was the coldest December in the six decades.

The last month of the 60-year period, December 2010 was an ECM at 13 stations in northwestern Europe (Fig. 4, Table 4). The temperature anomaly Δt in the west was approx. –3 to –4°C (with an average temperature t above zero) up to from –6 to –7°C in the Scandinavian Peninsula, with the greatest anomaly, $\Delta t = -7.3$°C, in Trondheim. In Valentia, Edinburgh and Copenhagen the deviation of average monthly temperature t from the 60-year average was higher than 3 standard deviations. The lowest temperature was $t = -9.2$°C in Oslo. For nearly all of the stations, it was the coldest December in the 60 years.

After 1986, all the ECMs were individual months, not related to extremely cold winter periods.

5. CONCLUSIONS

Extremely cold months (ECMs), understood as months with an average air temperature lower than the respective multi-annual average by at least 2 standard deviations, are quite frequent in Europe. During the 60-year period (1951-2010) there were 67 such months across the continent. However, most of the ECMs were limited in territorial extent to 1-3 stations out of the 60 stations included in the study, an extent that was recorded in as many as 40 ECMs. ECMs covering larger areas, more than 6 stations (*i.e.*, over 10% of the stations), only occurred in 20 months.

Overall, the greatest frequency of ECMs was recorded in the first two decades: half of all the ECMs (33) and over half of the cases (198 out of 387) were recorded before the 1969/70 season. The same years saw half of the ECMs with an extent of more than 10% of the stations, including the 3

ECMs with the greatest extent comprising over 20 stations: February 1954 (22 stations), February 1956 (36 stations), and January 1963 (25 stations). In the years that followed, ECMs occurred half as frequently, but their territorial extent was still significant in the decade of 1980/81−1989/90: January 1987 (23 stations) and January and February 1985 (19 stations each). ECMs were far less frequent in the last decade of the 20th century – only 7 months and 17 cases, but their frequency and range was on the rise again in the 21st century – in December 2001, 10 stations recorded the first ECM after 15 years, and for many stations it was the coldest December in the 60-year period. At the same time, the early 21st century experienced the highest frequency of extremely mild winter months in the entire six-decade period. Therefore, it can be concluded that despite the generally observable climatic warming, extremely cold winter months are still possible.

At the same time, it must be stressed that this applies to single months, and not whole winter periods, since only 32% of all the ECMs occurred during extremely cold winters, and the number of ECMs exceeded the number of such winters 3.75 times. Such relatively short-lasting and large drops in air temperature in winter are recorded across Europe, but are most frequent in central and northern parts of the continent. The greatest negative temperature anomalies at such times are recorded in eastern, and even more so in northeastern Europe where the average monthly temperature during ECMs may be lower than the average multi-annual temperature by 11-14°C.

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